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# NATURAL SAND BYPASSING AND RESPONSE OF EBB SHOAL TO JETTY REHABILITATION, OCEAN CITY INLET, MARYLAND, USA

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Ocean City Inlet, Maryland, is a dual-jetty inlet with a well-documented ebb shoal complex. During 2002, the south jetty was raised and sand tightened, and surveys in 2004 and 2005 show seaward radial migration of the outer ridge of the ebb shoal in response to the jetty rehabilitation. Natural sand bypassing occurs by transport from north to south. The ebb shoal contains a sand tongue on its northern extent that is maintained primarily by the ebb jet as it sweeps from south to north. Thus, transport that maintains the sand tongue is in the opposite direction from the natural bypassing, and growth of the sand tongue on its northwestern tip impinges on the navigation channel. Numerical modeling of tide and wave-driven circulation and sediment transport reproduces the morphologic processes that occur at Ocean City Inlet, and early modeling identified the sand tongue as a potential beach fill borrow site for mechanical bypassing to Assateague Island, as removal of sand there would not directly interrupt the natural bypassing pathway, and the material is not a source for Ocean City beaches to the north.

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## INTRODUCTION

Ocean City Inlet, MD, formed in August 1933 as a breach in the barrier island. Prior to the inlet breaching, Congress had authorized an inlet to be constructed approximately 8 km south of the new inlet to serve commercial navigation interests in the area. After reviewing the situation, Congress authorized stabilization of the new inlet, and north jetty construction began in September 1933. In response to the stabilized inlet, the up-drift shoreline on Fenwick Island to the north advanced, and the down-drift shoreline on northern Assateague Island receded 500 m (Dean and Perlin 1977), causing concern about integrity of the narrowed Assateague Island to overwash and breaching. The Coast & Geodetic Survey surveyed the pre-inlet offshore morphology in 1929, and numerous post-inlet surveys have been made through which formation of the ebb-shoal complex can be documented (Kraus 2000). Since January 2004, the Baltimore District of the U.S. Army Corps of Engineers has performed nine high-resolution surveys of the entire or portions of the ebb shoal (Fig. 1). The Baltimore District has maintained a directional wave gauge offshore of the inlet since 1994, and high-accuracy beach profiles surveys are made periodically along the beaches to the north and south. Availability of comprehensive morphologic response data makes Ocean City Inlet an excellent site for testing predictive numerical modeling technology.

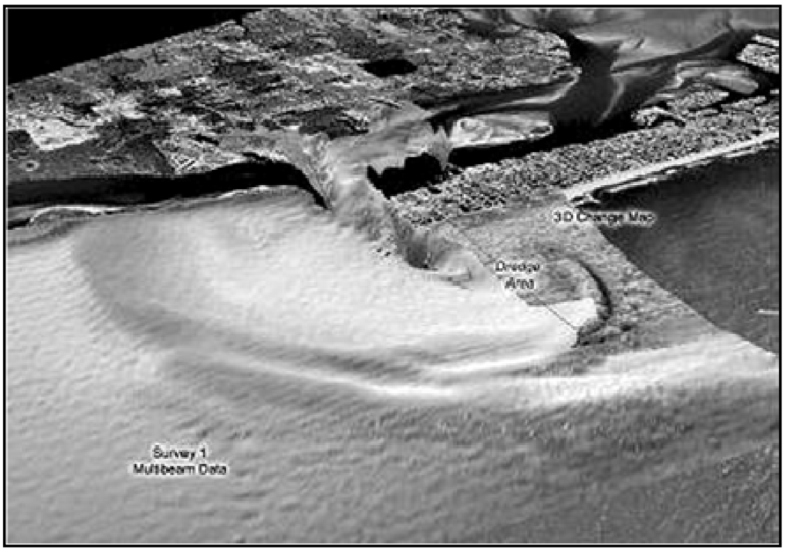


**Figure 1. Multi-beam survey of Ocean City Inlet and ebb shoal, April 2004.**

Since 2004, the Baltimore District in collaboration with the Assateague Island National Seashore, City of Ocean City, and other stakeholders has mechanically bypassed a nominal 138,000 $m^3$/year (180,000 cy/year) to northern Assateague Island, with the ebb shoal serving as the main borrow

source, supplemented by the flood shoal and an offshore site. The material is removed by the Corps' small hopper dredge Currituck with capacity of 230 $m^3$ (300 cy) and placed in the nearshore at 3-4.5-m depth. Numerical simulations with the Coastal Modeling System (CMS) have provided guidance on suitable areas for dredging of the ebb shoal. The numerical simulations include hydrodynamics, sediment transport, and morphology change under typical and storm conditions.

This paper describes observed morphology change and the numerical simulation methods and results, including (1) identification of an up-drift-directed tongue of sand projecting from the ebb shoal created by a strong ebb jet, (2) different sand bypassing pathways calculated under typical and storm wave conditions, and (3) observed morphology change showing radial expansion of the ebb shoal as a response to the 2002 rehabilitation of the south jetty.

## MORPHOLOGIC PROCESSES AT INLETS AND EBB SHOAL

Both natural processes and engineering activities have exerted control on the inlet, ebb shoal, and adjacent beaches at Ocean City Inlet. The area has been well surveyed, so that morphologic change through time can be documented.

### Engineering Activities and Long-Term Morphological Response

In August 1933, a hurricane opened Ocean City Inlet at the south end of the Ocean City boardwalk. A jetty on the north side of the inlet was built between September 1933 and October 1934, followed by the construction of the south jetty, which was completed in May 1935. Dredging of the inlet was completed in August 1935 to a controlling depth of 2.6 m (8.5 ft) MLW and a width of 61 m (200 ft) centered in the seaward portion of the inlet.

Within three years, the fillet on the north (up-drift) side of had reached the top of the north jetty, and sand entered the inlet. Consequently, the inshore section of the jetty was raised in 1937, and minor repairs were made to the south jetty by 1938. Following construction of the north and south jetties, erosion of northern Assateague Island increased as a result of sand deprivation owing to trapping of sediment by the north jetty. Inlet processes began forming ebb and flood shoals at the expense of the adjacent beaches. Through time, a crescentic ebb shoal formed and is offset to the south of the jetties. A two-part flood shoal also formed in the coastal bays north and south of the inlet. Increasing recession of Assateague Island resulted in erosion around the inshore end of the south jetty, which was repaired in 1956 by placement of about 845 tons of stone. Erosion of Assateague Island continued and by 1961 resulted in additional recession at the inshore section of the south jetty. By 1976, bathymetric surveys indicated that the ebb shoal had migrated southwestward. By the mid-1970s, an attachment bar formed between the ebb shoal and Assateague Island, allowing sediment to pass from the ebb shoal to the island beach. The probable combination of wave refraction around the ebb shoal and evolving orientation of

the offshore contours caused a net northbound longshore transport north of the attachment point. This tendency for northbound transport caused shoaling in the inlet as the sand was carried over, around, and through the low, permeable south jetty. Consequently, the inshore section of the south jetty was raised and sand tightened in December 1985. This promoted stability of the northern 1.5 km of Assateague Island and reduced shoaling in the inlet.

Several coastal projects in the area have continued to contribute to the evolution of the inlet and tidal shoal complex. In the early 1990s, a major storm protection beach nourishment project was constructed along 11 km of beach at Ocean City, providing an up-drift source of sand to the inlet. The project has been renourished at 4-year intervals beginning in 1994 with an average placement volume of about 600,000 $m^3$ (800,000 cy) of sand. In the late 1980s, placement of scour protection beneath the bridge connecting Ocean City to the mainland altered tidal flow throughout the area. Rapid development of shorefront structures, marinas, and entrance channels throughout the back bays has occurred since 1990. Rehabilitation of the outer leg of the south jetty was performed in 2002, which raised and sand-tightened that portion of the structure. The finished elevation of the jetty ranges between 1.52 m (5.0 ft) and 2.29 m (7.5 ft) NGVD29, which corresponds to 6.66 ft and 9.16 ft above MLW, respectively. A stone scour blanket was placed along the inside of the outer leg to fill and prevent continued development of a scour hole.

## Recent Morphology Change

Tidal inlets provide for the exchange of water, sediment, nutrients, and organisms between the ocean and back bays, with the morphology of inlets being constantly modified by changing waves, water level, and currents. Ocean City Inlet consists of a flood-tidal shoal, an ebb-tidal shoal complex, and a channel. The ebb shoal is formed of sand deposited primarily by ebb-tidal currents and wave-driven transport. Since the 1970s, natural bypassing has been partially re-established to Assateague Island through development of a bypassing bar and attachment bar (Kraus 2000), which are parts of the ebb-shoal complex.

Recent hydrographic survey data taken at Ocean City Inlet provide insight into the morphology change of the ebb shoal in response to rehabilitation of the south jetty in 2002 and focusing of the ebb-tidal jet. A pre-rehabilitation survey with a conventional single beam system was performed by the Baltimore District in 2000. In January 2004 and in August 2005, comprehensive post-rehabilitation swath surveys of the entire ebb shoal were performed. Since 2003, nine partial surveys have been performed to identify and monitor sediment sources for beach replenishment material bypassed to northern Assateague Island.

Swath bathymetry using beam-forming sonar technology allows for 100% seafloor coverage over a ribbon that is approximately four times the water depth. The advantage of multi-beam sonar over single beam is acquisition of

higher density data over the seabed (about 15 times higher). Greater resolution and across-track coverage compared to previous single beam surveys allow for a more accurate representation of contours and the most repeatable volume change analysis. Average resolution, quantified over 11 either comprehensive or partial surveys at Ocean City Inlet, is +/-0.037 m (Grosskopf et al. in prep.). Figure 2 shows the location of the comprehensive surveys performed in January 2004 and August 2005, as well as those of the nine partial surveys performed since 2003.

The most recent comprehensive multi-beam survey of the inlet and tidal shoal complex, performed in August 2005, is shown in Fig. 3, and morphology change from January 2004 and August 2005 is shown in Fig. 4. Obvious features include a deep east-west channel entering the inlet from the ocean, a semi-circular shaped ebb tidal shoal that is skewed to the south, indicating net longshore sediment transport is north to south, and the attachment bar on Assateague Island to the south. The scoured entrance channel narrows inside the inlet where a flood shoal is growing. Ebb-tidal currents appear to be pushing a wave of sediment seaward from the inlet in response to the rehabilitation of the outer leg of the south jetty. The outer ridge of the ebb shoal expanded radially as sand is being transported seaward from the inlet by the ebb current. The northern part of the ebb shoal exhibits a "tongue" that is impinging on the Ocean City beach and the navigation channel that runs in a north-south direction between the Ocean City beach and the tongue. This feature is attributed to sand that is driven toward the north by the ebb jet and transport by waves from the southeast. The attachment bar at the southern end of the survey area is being pushed to the south, and the area along the Assateague Island beach to the north is deepening. These data sets provide an accurate and consistent foundation for a hydrodynamic and morphologic numerical model application.


**Figure 2. Boundaries of multi-beam surveys performed since 2003.**

## NUMERICAL MODELING APPROACH

Numerical modeling of circulation, waves, and sediment transport was conducted within the CMS. Circulation and sediment transport were calculated with CMS-M2D (Militello et al. 2004; Buttolph et al. 2006), and wave propagation and transformation were calculated with WABED (Lin et al. 2006). CMS-M2D calculates depth-averaged current, water level, sediment transport, and morphology change in two horizontal dimensions. Model forcing can include any combination of wave radiation stress gradients, wind velocity, flow rate, water-surface elevation, and combined water-surface elevation and current velocity. Wave properties can also be input for calculation of wave friction, wave mixing, and wave-driven sediment transport. CMS-M2D contains three options for calculation of sediment transport and morphology change: Watanabe (1987) total load formulation, Lund-CIRP (Camenen and Larson 2005; Camenen and Larson 2007) total load formulation, and the advection-diffusion transport equation. CMS-M2D also has the capability to represent non-erodible substrate (hard bottom) in computing sediment transport and morphology change.

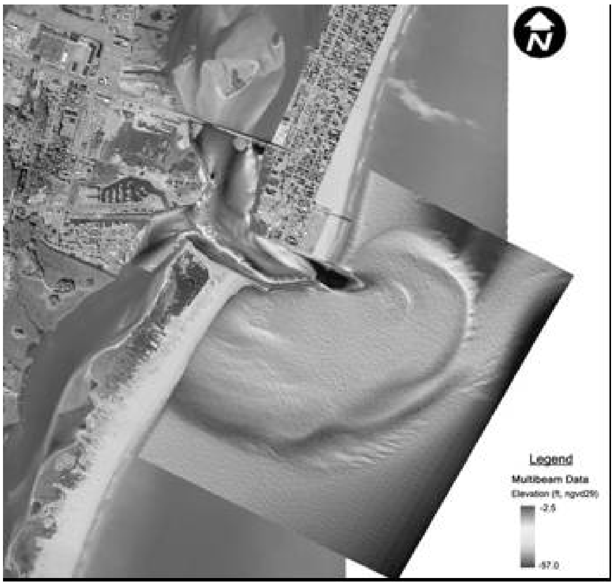


**Figure 3. Comprehensive survey of Ocean City Inlet and ebb shoal, August 2005.**

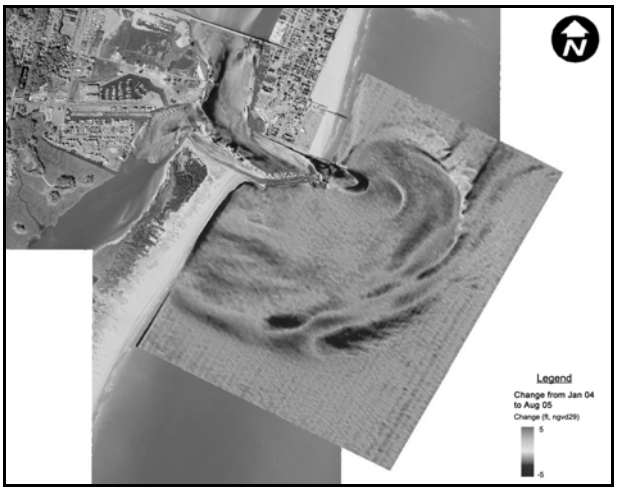


**Figure 4. Change in inlet and shoals from January 2004 to August 2005**

WABED is a two-dimensional, phased-averaged, half-plane spectral wave model that computes wave propagation and transformation. Wave spectra provided at offshore boundaries are propagated into the WABED domain. Local wind-generated waves can also be calculated by WABED if wind speed and direction are specified as model input.

Simulations are developed and run from within the Surfacewater Modeling System (SMS) on a PC. Interactions between CMS-M2D and WABED are

automatically controlled through a Steering Module in the SMS in which the user specifies the coupling between the wave and circulation models. The Steering Module allows input of time intervals, called steering intervals, at which CMS-M2D and WABED interact, and specification of information to be passed between the models. Interaction between models is conducted by mapping solutions from one model to the grid of the other and providing the mapped solution as input for the following steering interval. The SMS also provides for specification of wave properties and spectra generation, specification of CMS-M2D forcing input, sediment transport and morphology change options, and global and numerical station output. CMS-M2D and WABED were established at Ocean City Inlet with high resolution through the entrance, over the ebb shoal, and along the adjacent nearshore.

### Model Establishment and Forcing

The CMS-M2D and WABED models were built with bathymetry for the Atlantic Ocean and back-bay areas obtained from an existing regional ADCIRC mesh developed for Ocean City Inlet applications. Survey data from year 2000 for Ocean City Inlet and the ebb shoal were entered into the grids so that pre-rehabilitation bathymetry was prescribed as the initial morphologic condition. Design drawings of the jetty rehabilitation and scour blanket provided information for structural representation. The computational domain and bathymetry for CMS-M2D are shown in Fig. 5. Cell size ranges from 37.8 m to 182.5 m in the CMS-M2D grid, with greatest detail in the inlet. Wave-driven processes were computed at Ocean City Inlet and over the ebb shoal so that the WABED domain covers a smaller area than the CMS-M2D grid. The WABED domain overlays the M2D domain at the inlet and the Atlantic Ocean portion of the grid offshore of the inlet. Cell size for the WABED grid is 44.9 m.

Tide and wave forcing were applied for a 1-year time interval starting on January 1, 1997. This time period was selected because of the availability of directional wave data from NDBC buoy 44009, located near Delaware Bay. Wave data were processed such that waves traveling from the shoreward direction, out of Delaware Bay, were set to have wave height of 0.0 m. Tidal values were obtained from the 2001 Eastcoast ADCIRC tidal constituent database (Mukai et al. 2002) and were coincident in time with the wave data.

Sediment transport rates were computed with the Lund-CIRP total load formulation using a median grain size of 0.2 mm. The rehabilitated south jetty, scour blanket, and area under the Route 50 bridge were specified as hard bottom. These areas can accumulate sand, but cannot erode below a specified hard-bottom depth. Morphology change was calculated at 0.25-hr intervals.

Interaction between CMS-M2D and WABED was specified to take place every 3 hr. Radiation stress gradients and wave properties (height, period, direction, and wave dissipation) were supplied to CMS-M2D from WABED. Total water depth, which included calculated morphologic change, was provided to WABED from CMS-M2D.

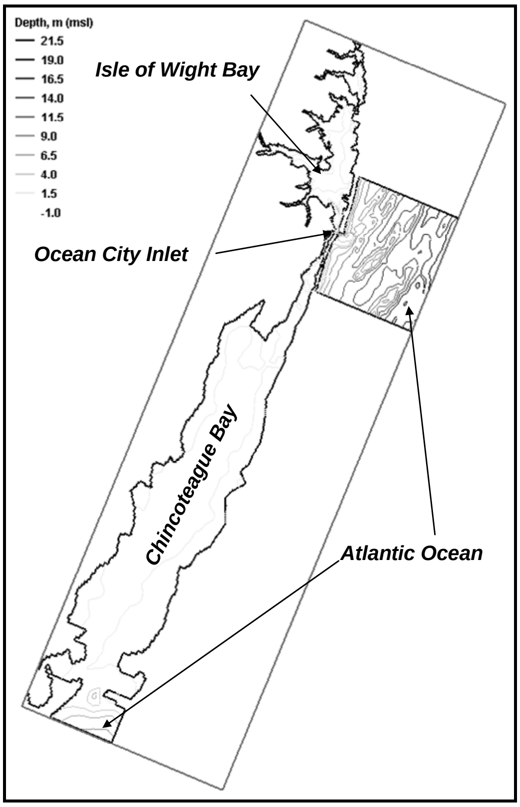


**Figure 5. Computational domain for CMS-M2D hydrodynamic and sediment transport calculations.**

## Simulation Results

Results of the numerical modeling are presented to investigate the physical processes that control the morphologic features at Ocean City Inlet and the ebb shoal, bypassing mechanisms, and the response of the inlet and ebb shoal to rehabilitation of the south jetty. This paper discusses results after 237 days of simulation.

Bypassing around Ocean City Inlet takes place primarily when waves arrive from the northeast. Longshore transport is directed southward and across the ebb shoal (Fig. 6). Bypassing by northeast wave-driven transport can take place under a broad range of wave heights, but is strongest during storms. When waves arrive from the southeast, bypassing to the north can occur (Fig. 7). However, larger waves from the southeast create complex transport patterns at the ebb shoal that can inhibit northward bypassing over portions of the shoal. During periods of weaker southeast waves, northward transport can take place

without being impeded by complex wave-driven currents that occur during storms; however, transport rates are weaker than during larger waves.

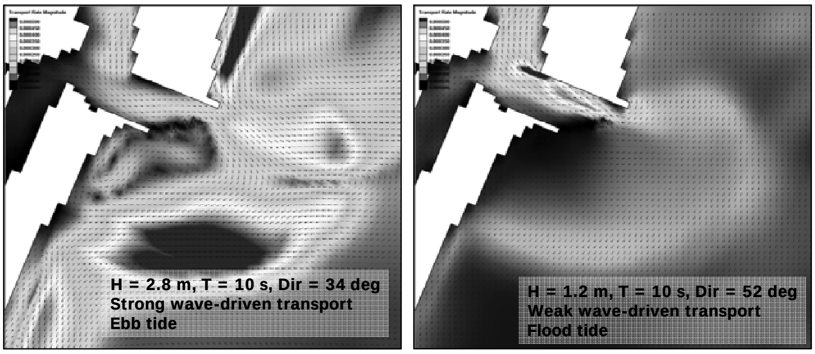


**Figure 6. Transport rate vectors for northeast waves.**

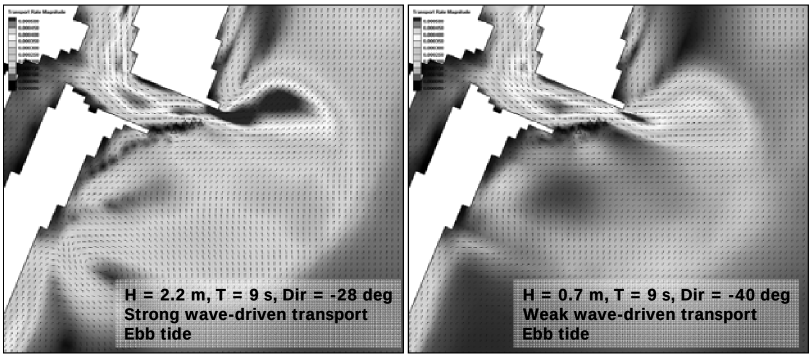


**Figure 7. Transport rate vectors for southeast waves.**

The ebb jet was identified as the key process controlling maintenance (if not formation) of the sand tongue located on the north side of the ebb shoal. Over the ebb portion of the tidal cycle, the ebb jet sweeps from south to north. The sand tongue is located where the outer ebb jet loses speed. Figure 8 shows a time sequence of transport rates calculated during the ebb cycle. Spatial deceleration at the tip of the ebb jet promotes deposition. The periodic nature of the ebb jet movement and structure provides a persistent process for maintenance of the sand tongue. This process can be modified during storms, when large waves drive strong currents, but it is present otherwise.

Natural bypassing at Ocean City Inlet moves sand from north to south. Under small waves from the north, sediment would tend to go into the channel, whereas under large waves, bypassing occurs over the ebb shoal. In contrast, action of the ebb jet is from south to north, depositing material on the sand tongue where the jet decelerates. Because the ebb jet process is tidal, occurring twice daily, maintenance of the sand tongue is persistent and does not rely on

storms or seasonal processes. Sand can be removed from the tongue for placement elsewhere, and the dredged area will be refilled with sand providing a renewable source of borrow material. In addition, removal of material from the tongue would not interfere with bypassing from the north.

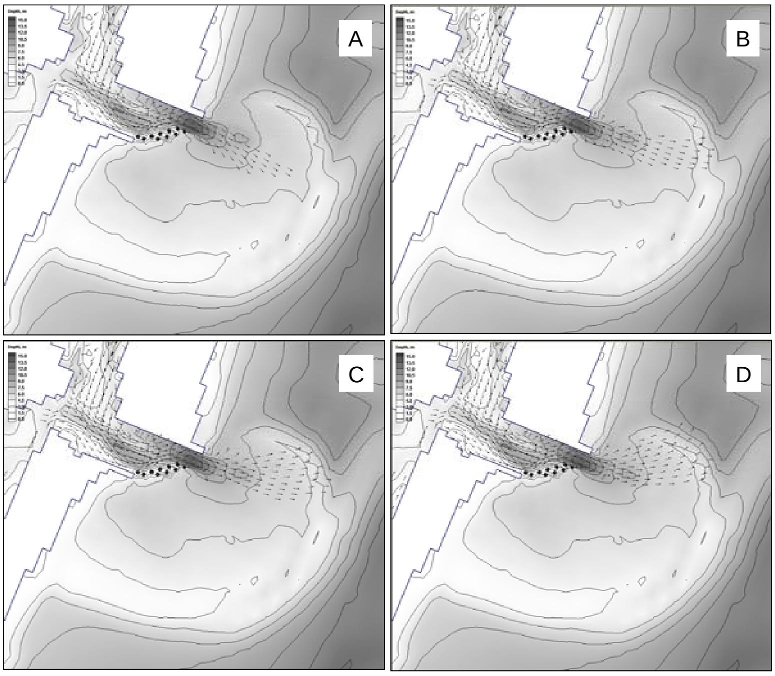


**Figure 8. Transport rates during ebb tide (time sequence is denoted by A, B, C, D).**

Rehabilitation of the south jetty in 2002 constricted flow at the inlet mouth to a greater extent than the pre-rehabilitated jetty. Since rehabilitation, the ebb jet has stronger current speed and transports material further from the inlet. Ebb shoal morphology expresses this response through radial expansion. Measured and calculated morphology changes are compared in Fig. 9 for the area that had overlapping coverage in the 2000 and 2004 surveys. This area includes the northern half of the inlet, but not the southern half. Measured change is for the 4-year interval from 2000 to 2004 and calculated change is for the 237 days of simulation time. At 237 days, the calculated morphology is still evolving. However, in comparing the measured and calculated morphology change, common patterns are present. The northern half of the inlet has shoaled. In addition, radial sand ridges have migrated seaward. Thus, the calculations are reproducing the response of the ebb shoal and the inlet to the jetty rehabilitation. Calculated morphology change also indicates shoal formation at the seaward end of the inlet. Measurements do not show such a well-developed shoal, but there appears to be small remnants of a depositional feature. Further calculation

of the morphology change is needed to determine if the calculated shoal is eroded as the features continue to evolve and approach equilibrium.

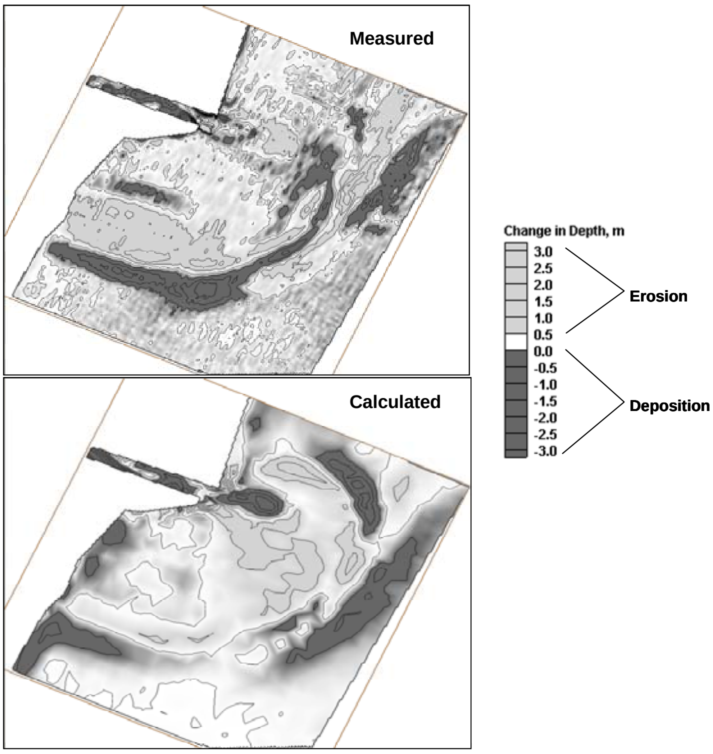


**Figure 9. Measured (2000 – 2004) and calculated (237 days) change in depth at Ocean City Inlet and ebb shoal.**

Initial bathymetry and calculated bathymetry after 237 days are shown in Fig. 10. Shoaling has occurred in much of the inlet, particularly the southern portion. In addition, the concentric sand ridges of the ebb shoal have begun to migrate radially seaward. Crests of the ebb shoal ridges are lower than the initial condition as the material is being eroded from the crests and deposited on the seaward side.

## CONCLUSIONS

Rehabilitation of the south jetty in 2002 has strengthened the ebb jet, causing the seaward ridge of the ebb shoal to migrate radially outward. Differences in measured bathymetry between the 2004 and 2005 surveys indicate that the shoal expansion may still be ongoing. Combined circulation, sediment transport, and wave modeling with the CMS reproduced the trend in shoal expansion owing to the jetty rehabilitation. Longer-term simulations than

the 237 days shown here can be conducted to estimate multi-year morphologic response.

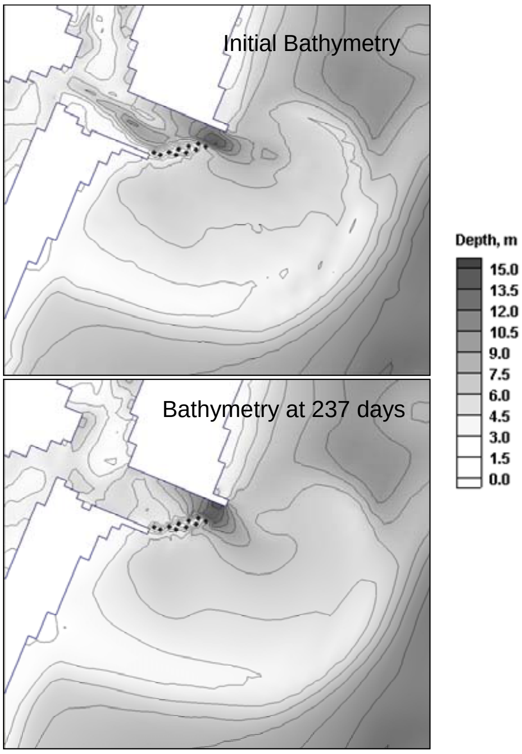


**Figure 10. Initial and calculated bathymetry at 237 days.**

Surveys revealed the presence of a permanent sand tongue on the northern end of the ebb shoal. Modeling of circulation and transport rates with CMS-M2D indicate that the sand tongue is maintained by the periodic presence of the ebb jet. The jet sweeps from south to north twice daily and decelerates at the location of the sand tongue, providing for a depositional environment. Bypassing takes place when waves arrive from the northeast. When waves are of sufficient strength, the wave-driven currents will carry sand across the inlet mouth and into the nearshore area to the south. Because the ebb jet is the process controlling the sand tongue, material dredged from the tongue will be replenished over time. This process supports survey data that suggest that the sand tongue is a reliable, renewable source of sand for beach replenishment on Assateague Island. Because the tidal processes responsible for maintaining the sand tongue are distinct from those wave-driven processes controlling bypassing, removal of material from the tongue will not interfere with natural bypassing.

The numerical models and high-resolution surveys at the inlet can serve as inlet-management tools. Surveys provide observations of morphologic response and also permit verification of model calculations. Model results can, in turn, be applied to evaluate engineering and dredging options.

## ACKNOWLEDGMENTS

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